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Citation for published version (APA):

Epro, G., McCrum, C., Mierau, A., Leyendecker, M., Brueggemann, G-P., & Karamanidis, K. (2018). Effects of triceps surae muscle strength and tendon stiffness on the reactive dynamic stability and adaptability of older female adults during perturbed walking. *Journal of Applied Physiology*, 124(6), 1541-1549. <https://doi.org/10.1152/jappphysiol.00545.2017>

Document status and date:

Published: 01/06/2018

DOI:

[10.1152/jappphysiol.00545.2017](https://doi.org/10.1152/jappphysiol.00545.2017)

Document Version:

Publisher's PDF, also known as Version of record

Document license:

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RESEARCH ARTICLE

Effects of triceps surae muscle strength and tendon stiffness on the reactive dynamic stability and adaptability of older female adults during perturbed walking

 Gaspar Epro,^{1,2}  Christopher McCrum,^{3,4} Andreas Mierau,^{5,6} Michael Leyendecker,⁵ Gert-Peter Brüggemann,^{2,7} and Kiros Karamanidis¹

¹Sport and Exercise Science Research Centre, School of Applied Sciences, London South Bank University, London, United Kingdom; ²Institute of Biomechanics and Orthopaedics, German Sport University Cologne, Cologne, Germany; ³NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, Department of Nutrition and Movement Sciences, Maastricht University, Maastricht, The Netherlands; ⁴Institute of Movement and Sport Gerontology, German Sport University Cologne, Cologne, Germany; ⁵Institute of Movement and Neurosciences, German Sport University Cologne, Cologne, Germany; ⁶Department of Exercise and Sport Science, LUNEX International University of Health, Exercise and Sports, Differdange, Luxembourg; and ⁷Cologne Center for Musculoskeletal Biomechanics, Medical Faculty, University of Cologne, Cologne, Germany

Submitted 12 June 2017; accepted in final form 26 February 2018

Epro G, McCrum C, Mierau A, Leyendecker M, Brüggemann GP, Karamanidis K. Effects of triceps surae muscle strength and tendon stiffness on the reactive dynamic stability and adaptability of older female adults during perturbed walking. *J Appl Physiol* 124: 1541–1549, 2018. First published March 1, 2018; doi: 10.1152/jappphysiol.00545.2017.—This study aimed to examine whether the triceps surae (TS) muscle-tendon unit (MTU) mechanical properties affect gait stability and its reactive adaptation potential to repeated perturbation exposure in older adults. Thirty-four older adults each experienced eight separate unexpected perturbations during treadmill walking, while a motion capture system was used to determine the margin of stability (MoS) and base of support (BoS). Ankle plantar flexor muscle strength and Achilles tendon (AT) stiffness were analyzed using ultrasonography and dynamometry. A median split and separation boundaries classified the subjects into two groups with GroupStrong ($n = 10$) showing higher ankle plantar flexor muscle strength (2.26 ± 0.17 vs. 1.47 ± 0.20 N·m/kg, means \pm SD; $P < 0.001$) and AT stiffness (544 ± 75 vs. 429 ± 86 N/mm; $P = 0.004$) than GroupWeak ($n = 12$). The first perturbation caused a negative Δ MoS (MoS in relation to unperturbed baseline walking) at touchdown of perturbed step (Pert_R), indicating an unstable position. GroupStrong required four recovery steps to return to Δ MoS zero level, whereas GroupWeak was unable to return to baseline within the analyzed steps. However, after repeated perturbations, both groups increased Δ MoS at touchdown of Pert_R with a similar magnitude. Significant correlations between Δ BoS and Δ MoS at touchdown of the first recovery step and TS MTU capacities ($0.41 < r < 0.57$; $0.006 < P < 0.048$) were found. We conclude that older adults with TS muscle weakness have a diminished ability to control gait stability during unexpected perturbations, increasing their fall risk, but that degeneration in muscle strength and tendon stiffness may not inhibit the ability of the locomotor system to adapt the reactive motor response to repeated perturbations.

NEW & NOTEWORTHY Triceps surae muscle weakness and a more compliant Achilles tendon partly limit older adults' ability to

effectively enlarge the base of support and recover dynamic stability after an unexpected perturbation during walking, increasing their fall risk. However, the degeneration in muscle strength and tendon stiffness may not inhibit the ability of the locomotor system to adapt the reactive motor response to repeated perturbations.

aging; falls; margin of stability; muscle strength; tendon stiffness

INTRODUCTION

Aging is associated with a gradual decline in the capacities of the entire neuromotor system, which leads to diminished mobility and reduced gait performance and hence to a decreased ability to produce effective and safe gait patterns during daily life. This can directly or indirectly lead to falls, which can have severe consequences such as adverse clinical conditions or even mortality (52). Approximately one-third of older adults fall at least once a year, and these falls occur most frequently during locomotion, usually due to tripping or slipping (4, 51). As well as daily-life falls, deficient stability control has also been demonstrated in laboratory settings using mechanical gait perturbations (e.g., sudden surface changes and trips) in older adults (7, 42, 49).

Gait stability can be controlled via reactive (feedback-driven) or predictive (feedforward-driven) adjustments (5, 8, 9, 25, 30, 32). Predictive adjustments are made on the basis of prior experience and knowledge about potential changes in the external environment, whereas reactive adjustments rely on the real-time sensory feedback received during movement (5, 8, 9, 29, 38, 40). Older adults, compared with younger adults, show less effective reactive adjustment in dynamic stability, mainly due to a reduced ability to effectively increase the base of support (BoS) following a gait perturbation (49). Given the importance of these predictive and reactive mechanisms for maintaining stability, it is promising that these mechanisms show improvement in response to repeated mechanical perturbations in healthy older adults (7–9, 12, 30, 33, 37, 39).

Address for reprint requests and other correspondence: G. Epro, Sport and Exercise Science Research Centre, School of Applied Sciences, London South Bank Univ., 103 Borough Rd., London SE1 0AA, UK (e-mail: g.epro@lsbu.ac.uk).

However, the rate of the adaptive improvement (at least in feedforward adaptation) seems to be diminished in older adults (12, 30). Therefore, the assessment of adaptation to repeated perturbations may provide useful insight into gait stability control in groups with reduced neuromotor capacities.

The age-related degeneration of the muscle-tendon unit (MTU) capacities, primarily the declined muscle strength and reduced tendon stiffness (14, 20, 26, 35, 48), are often linked to the reduced locomotor capacities. For instance, the age-related deterioration in muscle strength has been associated with diminished mobility in older populations (3, 24), as well as with a decreased ability to recover following a loss of balance (18, 23, 44, 45). In particular, inadequate recovery responses after tripping have been linked to age-related deficits in the ankle plantar flexion moment during the push-off phase (41–43). Older fallers show lower rates of torque development in all the support limb joints and a lower peak ankle moment, which contribute to an insufficient reduction of the angular momentum during push-off and create less proper placement of the recovery limb after induced tripping compared with younger or older nonfallers (42, 43). Furthermore, it has been shown that lower leg-extensor muscle strength and tendon stiffness are associated with deficits in balance recovery following a forward loss of balance in older adults (21, 23). These results imply that the triceps surae (TS) MTU mechanical properties in particular play an essential role in the recovery response to sudden gait disturbances, indicating that greater ankle plantar flexor muscle strength and Achilles tendon (AT) stiffness may be beneficial for gait stability in the elderly.

Although it has been shown that the ability to generate appropriate joint moments in the support limb during push-off may influence stability recovery following gait perturbations (41, 42), it has not yet been thoroughly investigated whether TS MTU mechanical properties are associated with gait stability and adaptability during repeated perturbations in older adults. In a previous study (16), we divided a group of older female adults into a strong and a weak group according to their ankle plantar flexor muscle strength and showed that the stronger older adults also possessed a higher AT stiffness. In the present study, we analyzed dynamic gait stability during perturbed walking in the same subject groups and thereby aimed to examine whether TS MTU mechanical properties are associated with the recovery responses and reactive adaptation potential in dynamic stability during perturbed walking in older adults. It was hypothesized that 1) a greater BoS and margin of stability (MoS) at touchdown (TD) of the first recovery step would be associated with the TS MTU mechanical properties, 2) older adults with greater ankle plantar flexor muscle strength and AT stiffness would regain balance after a perturbation during walking more effectively, and 3) the stronger older adults would show more pronounced improvement in the reactive response following repeated exposure to unexpected perturbations than their weaker counterparts.

MATERIALS AND METHODS

Participants. Thirty-four older female adults (age 65 ± 7 yr, body mass 65 ± 9 kg, body height 165 ± 6 cm, means \pm SD) from a large-scale knee osteoarthritis study (moderate unilateral knee osteoarthritis with Kellgren-Lawrence score 2–3; no pain during locomotion) voluntarily participated in the study. Exclusion criteria were any other neurological or musculoskeletal impairments of the lower limbs

(e.g., joint pain during locomotion) that might influence the findings of the study. The subjects were generally healthy compared with normative age group data [36-Item Short Form Health Survey (SF-36) general health questionnaire average outcome of 73.5%; average single-leg stance time of 39.6 s out of maximal 45-s test duration; mean timed up-and-go test result of 7.2 s]. All participants received medical clearance from their general practitioners prior to the measurements and provided their written informed consent after the procedures and possible risks of the study were explained. The study was approved by the ethics committee of the German Sport University Cologne and met all requirements for human experimentation in agreement with the Declaration of Helsinki.

Analysis of ankle plantar flexor muscle strength and AT stiffness. The method used to examine the mechanical properties of the TS MTU in vivo has been previously described in detail (16). Briefly, to determine ankle plantar flexor muscle strength, all subjects were placed in a seated position with their preferred leg for step initiation fixed, with ankle and knee joints flexed at 90° (thigh and foot perpendicular to the shank) and their feet placed on a custom-made strain gauge dynamometer (sampling frequency 1,000 Hz; Precision Engineering and Electronics Department of the German Sport University Cologne). Following a standardized warm-up (27), which consisted of 10 submaximal and 3 maximal voluntary isometric ankle plantar flexion contractions (MVCs), the subjects performed 6 separate MVCs with verbal encouragement (3 contractions “as strong as possible” and 3 controlled ramp contractions). The resultant ankle joint moments were calculated using inverse dynamics by accounting for the gravitational moments using a passive measurement (16). The individual ankle plantar flexor muscle strength (maximal plantar flexion moment) was assessed by considering all six performed MVC plantar flexion contractions and was normalized to the subject’s body mass (N·m/kg) to ensure an appropriate comparison. The contributions of the other synergistic muscles or the antagonist dorsiflexors were not accounted for; thereby the resultant plantar flexion moment is an approximation of the moment produced by the TS muscle. The mean values of the three MVC ramp contractions were used to determine the force-length relationship of the AT. For each participant, the AT moment arm was individually assessed using the tendon excursion method with the aid of ultrasonography during passive ankle joint rotation (28). The displacement of the myotendinous junction of the gastrocnemius medialis muscle (GM) during the passive movements and ramp contractions was analyzed with a linear array ultrasound probe (frequency 29 Hz; ultrasound device: MyLab Five; Esaote, Genoa, Italy). The displacement of the myotendinous junction in relation to a skin marker was manually digitized using Simi Motion 5.0 video analysis software (Simi Reality Motion Systems, Unterschleißheim, Germany). The effect of inevitable ankle joint angular rotation on the measured tendon elongation during each contraction was taken into account using a potentiometer located under the heel to calculate changes in the ankle joint angle as described previously (1, 16). Subsequently, the AT force was calculated by dividing the resultant ankle joint moment by the individual tendon moment arm. The stiffness of the AT was determined as the slope of the calculated tendon force and resultant tendon elongation between 50 and 100% of maximum tendon force using linear regression (16).

Analysis of the recovery response and reactive gait adaptation during perturbed walking. On a second measurement day, a gait perturbation paradigm was applied while walking on a treadmill using a manually controlled custom-built pneumatic brake-and-release system, similar to the magnetic system described in previous studies (30, 32, 49), which applies and removes resistance (generating ~ 55 N, within ~ 20 ms) to the lower right limb during walking via an ankle strap and Teflon cable. A treadmill-walking familiarization session was conducted for all subjects 4–7 days before the measurement day. During the measurement, all subjects walked at 1.4 m/s on a motor-driven treadmill (Pulsar 4.0; h/p/cosmos, Nussdorf-Traunstein, Ger-

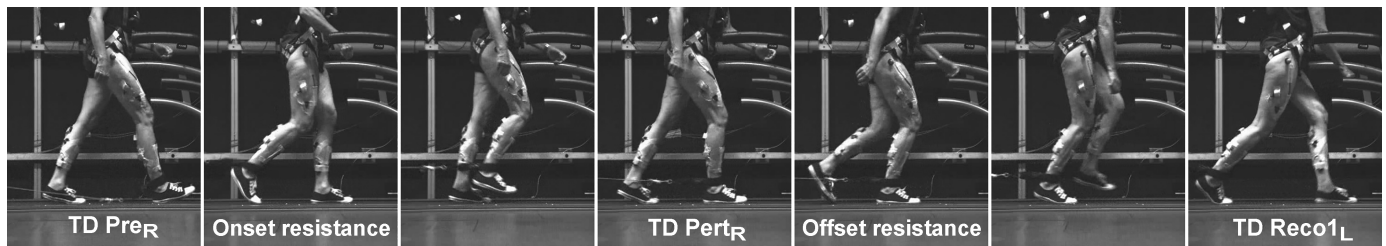


Fig. 1. A typical recovery response to the trip perturbation in one participant. The pull from the pneumatic brake-and-release system was activated (Onset resistance) during the support phase of the right leg and deactivated (Offset resistance) during the following support phase of the same leg; thereby the subject only experienced the pull during the swing phase of that leg. This caused a reduction in the base of support at foot touchdown (TD Pert_R) and a more anterior position and higher forward velocity of the center of mass in relation to unperturbed walking (TD Pre_R), hence leading to a decreased margin of stability. To maintain dynamic stability, the base of support needed to be increased in the following recovery step (TD Reco1_L).

many) and were secured with a safety harness connected to an overhead frame. To attain a natural gait pattern, all participants wore their own regular sports shoes. Similar to our previous protocols (30–32, 49), a separate baseline measurement (unperturbed walking) was recorded after 4-min walking (22) while wearing the ankle strap (with a negligible external resistance of ~0.1 N), from which 12 consecutive steps were used to determine the baseline parameters. Directly after this baseline measurement, the external resistance (55 N) was applied unexpectedly during an entire swing phase of the right leg, provoking a gait perturbation (Fig. 1). The application of the resistance over the entire swing phase assured an individually standardized perturbation from the temporal perspective for each participant. This unexpected perturbation was repeated eight times (trials), separated by washout periods of unperturbed walking of varying lengths of ~2–3 min, with the first (*trial 1*), fourth (*trial 4*), and eighth (*trial 8*) trials being considered for further analysis (Fig. 2). The participants were not informed about the onset or removal of the resistance but were aware that their gait was going to be perturbed at some point during walking.

To analyze dynamic stability during treadmill walking, a reduced kinematic model [adapted from Süptitz et al. (49)] was used. Five retroreflective markers (radius 16 mm) attached to anatomical landmarks [7th cervical vertebra (C7), greater trochanter of the left and right leg, and left and right hallux] were tracked at a frequency of 120 Hz using a motion capture system (Nexus; Vicon Motion Systems, Oxford, United Kingdom). The three-dimensional coordinates of the markers were smoothed using a fourth-order digital Butterworth filter with a cutoff frequency of 20 Hz. Each foot TD was detected using two-dimensional accelerometers (ADXL250; Analog Devices, Norwood, MA) placed on the tibias (50), whereas each foot toe-off was

determined by using the trajectories of the foot markers (41). A valid method to analyze biomechanical stability of human walking (11), the margin of stability (MoS) was calculated in the anteroposterior direction during gait at each foot TD (Fig. 2) according to the extrapolated center-of-mass concept (19), as the difference between the anterior boundary of the base of support (BoS; anteroposterior component of the toe projection to the ground) and the extrapolated center of mass (X_{CoM}), adapted for the simplified kinematic model based on Süptitz et al. (49)

$$X_{CoM} = P_{Tro} + \frac{\frac{(v_{Tro} + v_{C7})}{2} + |v_{BoS}|}{\sqrt{\frac{g}{L}}}$$

where P_{Tro} is the average horizontal (anteroposterior) component of the projection of the trochanter markers to the ground, v_{Tro} is the average horizontal velocity of the trochanter markers, v_{C7} is the horizontal velocity of the C7 marker, v_{BoS} is the horizontal velocity of the anterior boundary of the base of support (roughly equivalent to the velocity of the treadmill, as it is the average velocity of the forefoot marker during the stance phase), g is the acceleration due to gravity, and L is the average distance between the trochanter and the ankle joint center of rotation of the left and right legs in the sagittal plane, measured in a standing reference position. This adapted reduced kinematic model (49) has been shown to be appropriate to assess dynamic stability parameters (X_{CoM} , MoS, and BoS) in a wide range of age groups with negligible differences compared with a full body kinematic model, thus reducing data analysis and data processing.

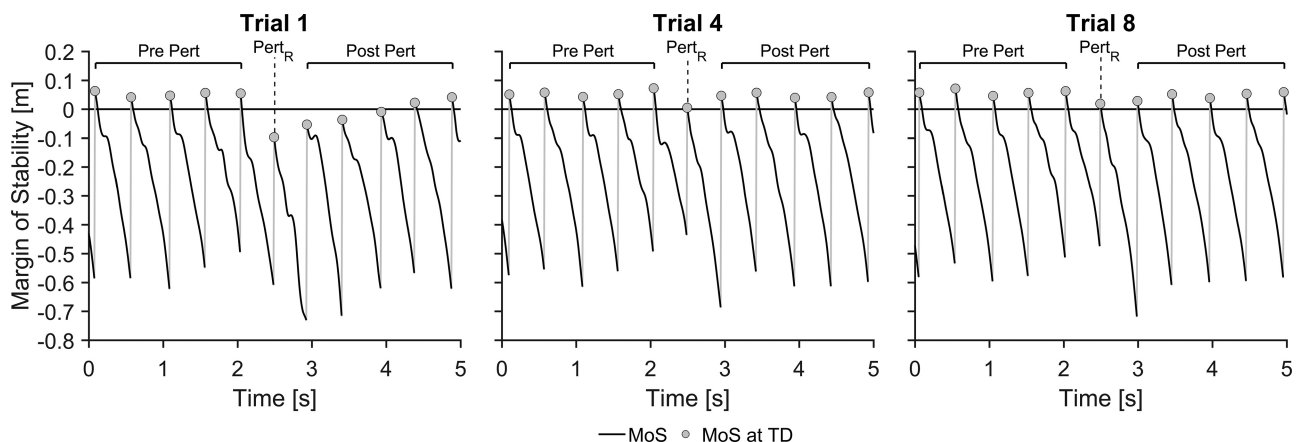


Fig. 2. Margin of stability (MoS) trajectories of one subject during five steps before (Pre Pert) and five steps after (Post Pert) the unexpected perturbation (Pert_R) in the first (*trial 1*), fourth (*trial 4*), and eighth (*trial 8*) gait perturbation trials. The circles represent the MoS values at the instances of touchdown (TD) of the corresponding leg.

Furthermore, to evaluate task demand during walking at the selected velocity (1.4 m/s) during perturbations, we additionally determined maximal walking velocity for each participant during over-ground walking over a 15-m walkway using the motion capture system (120 Hz) and two force plates (60 × 40 cm, 1,080 Hz; Kistler, Winterthur, Switzerland). The two force plates were used for a real-time check of the double-support phase. The left and right greater trochanters were tracked within a 3-m distance in the center of the laboratory. The maximal value of the average horizontal velocity of the trochanter markers in five valid (double support present) walking trials was selected as the individual maximal walking velocity.

Analysis of the electromyographic activity of the ankle plantar flexors during perturbed walking. The electromyographic (EMG) activity of soleus muscle (SOL) and GM of the right limb was recorded at a sampling rate of 1,080 Hz with adhesive bipolar surface Ag/AgCl electrodes (Blue Sensor; Ambu, Bad Nauheim, Germany) by using a telemetric EMG system (m320; myon, Schwarzenberg, Switzerland). The skin over the muscle belly was carefully shaved and cleaned with ethanol to reduce skin impedance. The electrodes were placed over the midpoint of the muscle belly, parallel to the assumed direction of the muscle fibers, and further secured to the skin along with the transmitter using an elastic tape to minimize motion artifacts. The raw EMG signals were band pass filtered (10–500-Hz Butterworth 4th-order recursive filter), full-wave rectified, and smoothed with a root-mean-square envelope using a 20-ms moving window. The filtered EMG data were separated into ground contact phases (time period between the foot TD and toe-off) and normalized to the full length of the ground contact phase and to the maximal activation during six consecutive contacts in the baseline walking for each muscle (relative EMG activity; EMG_{norm}). As the joint moment generation at ankle joint during the perturbed step ($Pert_R$) stance phase may be an important determinant of the BoS at the first recovery step ($Reco1_L$), the EMG_{norm} was analyzed at baseline walking (average of 6 consecutive right foot contact phases) and during the contact phase of $Pert_R$ in the analyzed perturbation trials (*trials 1, 4, and 8*; Fig. 3). To specifically examine the ankle push-off phase during walking, the mean EMG_{norm} from 50 to 100% of the ground contact phase was calculated. To assess the changes in relation to the baseline, we subtracted the mean EMG_{norm} during unperturbed walking in both analyzed muscles (ΔEMG_{SOL} and ΔEMG_{GM}).

Statistics. The analyzed older female adults were classified into two groups (GroupStrong and GroupWeak) based on their normalized maximal isometric ankle plantar flexion moment (N·m/kg) by using a median split and separation boundaries allowing for a minimum of 15% difference between the weakest subject of GroupStrong and the strongest subject of GroupWeak. Implementing this method led to a decrease in the overall number of subjects ($n = 22$) but allowed a clear separation between the groups. The distribution normality of all variables was checked before applying statistical analysis using the

Shapiro-Wilk test, which revealed normal distributions for all parameters ($P > 0.05$). Independent-samples *t*-tests were used to examine possible differences between GroupStrong and GroupWeak in size (body height and mass), age, ankle plantar flexor muscle strength, AT stiffness, and maximal walking velocity. Additional independent-samples *t*-tests were implemented to determine potential differences in MoS and BoS during unperturbed baseline walking (average of 12 consecutive steps of unperturbed walking with the ankle strap) between the two subject groups. To examine the recovery response during perturbed walking, the MoS and BoS at TD of $Pert_R$ and of the following first six recovery steps ($Reco1_L$, $Reco2_R$, $Reco3_L$, $Reco4_R$, $Reco5_L$, and $Reco6_R$) of *trial 1* were investigated. Furthermore, to account for individual differences in walking stability, the change in the MoS and BoS relative to baseline unperturbed walking at $Pert_R$ and the following six recovery steps was used (ΔMoS and ΔBoS), where negative ΔMoS and ΔBoS values indicate smaller MoS and BoS in relation to steady-state (unperturbed) walking, respectively. To identify potential differences in ΔMoS and ΔBoS , a two-way repeated-measures analysis of variance (ANOVA) was implemented with the subject group (GroupStrong and GroupWeak; independent variable) and step ($Pert_R$, $Reco1_L$, $Reco2_R$, $Reco3_L$, $Reco4_R$, $Reco5_L$, and $Reco6_R$; dependent variable) as factors. For the analysis of the adaptation potential of the reactive recovery response, the ΔMoS at TD of $Pert_R$ was analyzed in *trials 1, 4, and 8*. Therefore, a two-way repeated-measures ANOVA was implemented for ΔMoS at TD of $Pert_R$ with subject group as an independent variable and the perturbation trial as the dependent variable. When a significant group, step, trial, or interaction effect was detected by the ANOVAs, Tukey's post hoc test was implemented for pairwise comparisons. Regarding the EMG activity of $Pert_R$, further separate two-way repeated-measures ANOVAs were performed with the mean EMG_{norm} during the second phase of the ground contact phase (push-off/propulsion phase) for both analyzed muscles (ΔEMG_{SOL} and ΔEMG_{GM}) with the subject group (GroupStrong and GroupWeak; independent variable) and perturbation trial (*trials 1, 4, and 8*; dependent variable) as factors. Furthermore, the Pearson product-moment correlation coefficient and a multiple-regression analysis were implemented to identify the relationship between TS MTU capacities and dynamic stability control, by using the ankle plantar flexor muscle strength and AT stiffness, and the ΔMoS and ΔBoS at TD of the first recovery step ($Reco1_L$) of *trial 1* with the participants from the newly formed groups ($n = 22$). All statistical analyses were performed using STATISTICA (version 10; StatSoft, Tulsa, OK). The significance level was set at $\alpha = 0.05$, with results in text and figures presented as means and SD.

RESULTS

GroupStrong ($n = 10$), compared with GroupWeak ($n = 12$), had, on average, ~43% higher maximal isometric ankle plantar

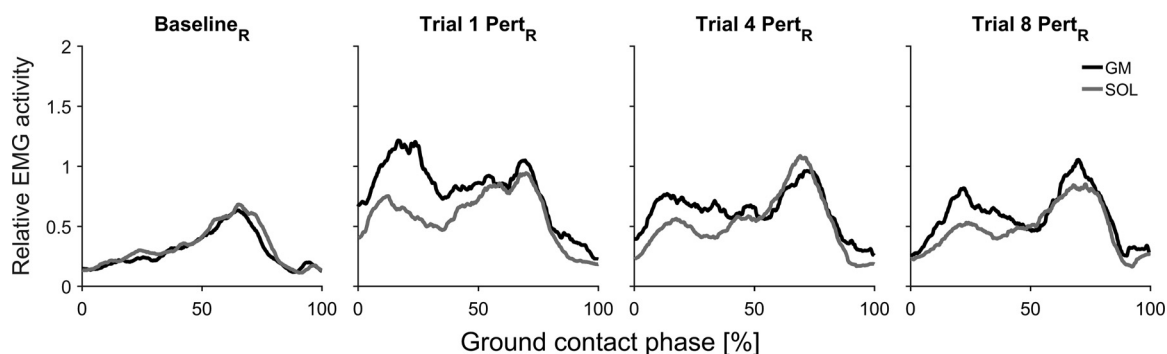


Fig. 3. Electromyographic (EMG) activity of soleus muscle (SOL) and gastrocnemius medialis muscle (GM) during the ground contact phase of the right limb during unperturbed walking ($Baseline_R$) and of the perturbed right step ($Pert_R$) in all three analyzed perturbation trials (*trials 1, 4, and 8*; $n = 22$). EMG activity data were normalized to the maximal EMG activity determined for the corresponding muscle during unperturbed walking.

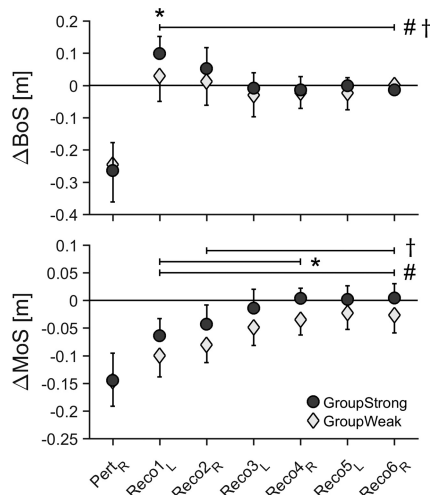


Fig. 4. Change relative to baseline unperturbed walking in base of support (ΔBoS) and margin of stability (ΔMoS) at touchdown (TD) of the perturbed step (Pert_R) and at TD of the first six recovery steps following the perturbation (Reco1_L – Reco6_R) in the stronger (GroupStrong, $n = 10$) and weaker (GroupWeak, $n = 12$) groups in the first perturbation trial (*trial 1*). All values are expressed as means with SD (error bars). *Statistically significant difference between GroupStrong and GroupWeak ($P < 0.05$). #Statistically significant difference compared with Pert_R for GroupStrong ($P < 0.05$). †Statistically significant difference compared with Pert_R for GroupWeak ($P < 0.05$).

flexion moment (2.26 ± 0.17 vs. 1.47 ± 0.20 N·m/kg; $P < 0.001$) accompanied by a 24% higher AT stiffness (544 ± 75 vs. 429 ± 86 N/mm; $P = 0.004$). Furthermore, GroupStrong demonstrated ~11% higher maximal walking velocity than GroupWeak (2.54 ± 0.15 vs. 2.27 ± 0.21 m/s; $P = 0.003$). There were no significant differences between the groups in age (GroupStrong: 64 ± 5 vs. GroupWeak: 65 ± 6 yr), body mass (63 ± 11 vs. 68 ± 7 kg), or body height (166 ± 8 vs. 165 ± 5 cm).

Regarding the gait stability parameters during baseline walking, no significant differences were found between the subject

groups either in MoS (0.04 ± 0.03 vs. 0.04 ± 0.04 m for GroupStrong and GroupWeak, respectively) or in BoS (0.63 ± 0.04 vs. 0.65 ± 0.04 m). Concerning the analysis of the reactive recovery response during the first unexpected perturbation trial (*trial 1*), the two-way repeated-measures ANOVA revealed a statistically significant subject group and step interaction for ΔMoS , meaning that the effect of subject group on dynamic stability control was step specific. The gait perturbation caused considerable decrease in MoS and BoS (Fig. 4) in both subject groups, with the post hoc tests revealing no significant group differences in ΔMoS or ΔBoS at TD of Pert_R . GroupWeak demonstrated significantly lower ΔMoS (more negative values) compared with GroupStrong for the first four analyzed recovery steps ($0.034 < P < 0.043$; Fig. 4). Following the perturbation, GroupStrong showed significantly higher ΔMoS values compared with Pert_R in all analyzed recovery steps ($0.0001 < P < 0.004$; Fig. 4), thereby requiring four recovery steps to return to MoS baseline (zero level). GroupWeak demonstrated significantly ($P < 0.01$; Fig. 4) higher ΔMoS values compared with Pert_R starting from the second recovery step (Reco2_R) but failed to recover to MoS baseline within the observed six recovery steps (did not reach ΔMoS zero level). For the ΔBoS values, the two-way repeated-measures ANOVA resulted in a group and step interaction. The post hoc comparison revealed a significantly ($P < 0.001$; Fig. 3) higher ΔBoS at TD of all recovery steps compared with Pert_R in both groups, with GroupStrong showing a significantly ($P = 0.042$) higher ΔBoS at TD of Reco1_L than GroupWeak (0.10 ± 0.05 vs. 0.03 ± 0.04 m; Fig. 4).

Significant correlations were identified between the TS MTU mechanical properties and ΔBoS at TD of Reco1_L ($r = 0.57$, $P = 0.006$ and $r = 0.53$, $P = 0.012$ with maximal isometric ankle plantar flexion moment and AT stiffness, respectively; $n = 22$; Fig. 5) and for ΔMoS at TD of Reco1_L ($r = 0.50$, $P = 0.019$ and $r = 0.41$, $P = 0.048$; $n = 22$; Fig. 5). The multiple-regression analysis revealed a significant rela-

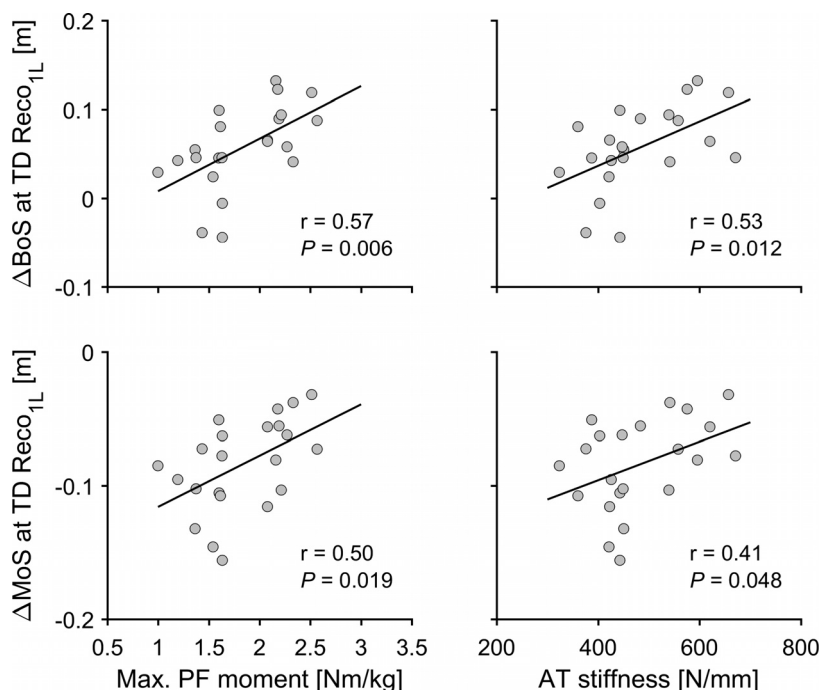


Fig. 5. Top: relationship between the change in base of support (ΔBoS) at touchdown (TD) of the first recovery step (Reco1_L) and maximal ankle plantar flexor moment (Max. PF moment) and Achilles tendon (AT) stiffness ($n = 22$). Bottom: relationship between the change in margin of stability (ΔMoS) at TD of Reco1_L and maximal ankle plantar flexor moment and AT stiffness ($n = 22$).

tionship between ankle plantar flexor muscle strength and AT stiffness and the stability measures, with ΔBoS at TD of Reco1_L ($R^2 = 0.37$, $P = 0.015$; $n = 22$) as well as with ΔMoS at TD of Reco1_L ($R^2 = 0.27$, $P = 0.044$; $n = 22$).

Concerning the analysis of the repeated gait perturbations, the two-way ANOVA with subject group and perturbation trial (*trials 1, 4, and 8*) as factors revealed a significant perturbation trial effect on ΔMoS ($P < 0.001$) but no significant subject group effect or interaction (Fig. 6). The post hoc tests showed that repeating the gait perturbation resulted in a significant ($P < 0.001$) increase in ΔMoS at TD of Pert_R in both GroupStrong and GroupWeak, with no between-subject group differences (Fig. 6). No significant differences in ΔMoS at TD of Pert_R were found between *trials 4* and *8*, in either of the subject groups (no significant interaction effect).

Regarding the mean EMG_{norm} during the second phase of the ground contact phase (50–100% of the ground contact phase) of Pert_R in SOL and GM in *trials 1, 4, and 8*, a significant subject group effect was determined for GM with higher ($P = 0.038$) $\Delta\text{EMG}_{\text{GM}}$ for GroupStrong compared with GroupWeak, regardless of the analyzed perturbation trial (Fig. 7). No significant group differences were found in $\Delta\text{EMG}_{\text{SOL}}$ during the second phase of the ground contact phase (push-off phase) of Pert_R .

DISCUSSION

This study aimed to examine whether TS MTU mechanical properties are associated with the recovery response and the reactive adaptation potential in dynamic stability during perturbed walking within a homogenous group of older adults. Our first hypothesis, that the BoS at TD of the first recovery step is associated with the TS MTU mechanical properties, was partly confirmed with a moderate correlation. Furthermore, the hypothesis that stronger older adults have a more effective recovery response than weaker older adults could be likewise confirmed, as the stronger adults needed fewer recovery steps to regain dynamic stability after a sudden perturbation than their weaker counterparts. However, our third hypothesis, that older adults with greater ankle plantar flexor muscle strength and AT stiffness show more pronounced improvement in the reactive response following repeated exposure to unexpected perturbations than their weaker counterparts, was rejected, as

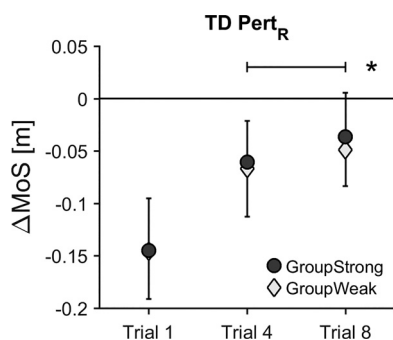


Fig. 6. Change relative to baseline unperturbed walking in margin of stability (ΔMoS) at touchdown (TD) of the perturbed step (Pert_R) and in the first recovery step (Reco1_L) in the first (*trial 1*), fourth (*trial 4*), and eighth (*trial 8*) perturbation trials for the stronger (GroupStrong) and weaker (GroupWeak) subject groups. All values are expressed as means with SD (error bars). *Statistically significant differences compared with *trial 1* ($P < 0.05$).

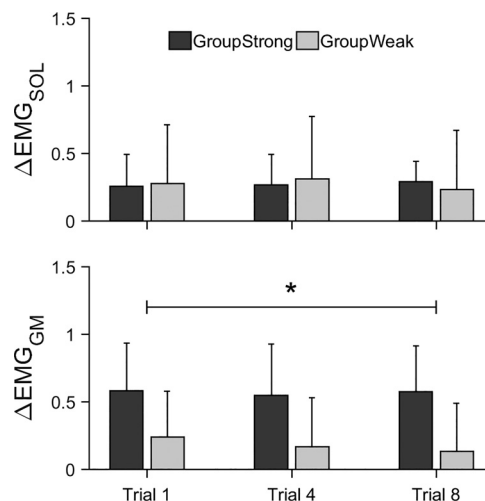


Fig. 7. Change relative to baseline unperturbed walking in electromyographic activity of soleus muscle ($\Delta\text{EMG}_{\text{SOL}}$) and gastrocnemius medialis muscle ($\Delta\text{EMG}_{\text{GM}}$) during the push-off phase (defined by examining 50–100% of the ground contact phase) of the perturbed step (Pert_R) in the analyzed perturbation trials (*trials 1, 4, and 8*). *Statistically significant difference between GroupStrong and GroupWeak ($P < 0.05$).

no differences in reactive adaptation potential were seen between the stronger and weaker groups of older adults.

Following the unexpected gait perturbation, GroupStrong was able to produce a larger first recovery step in the anterior direction (higher ΔBoS) than GroupWeak (Fig. 4). As a result, GroupStrong could create a more advantageous body position at the first recovery step than GroupWeak, thereby influencing the dynamic stability control in the following recovery steps. Consequently, the stronger older female subjects returned to the ΔMoS baseline (zero ΔMoS) at the fourth recovery step following the perturbation, whereas the weaker group showed less effective recovery behavior and did not return to baseline ΔMoS within the observed six recovery steps (Fig. 4). Similar decreased ability to recover following a loss of balance due to age-related deterioration in the MTU capacities has been identified in various perturbations (slips and trips) or in sudden forward falls from an inclined position in older compared with younger adults (18, 23, 42–44, 49). Similar to the present study, these contrasts were mainly attributed to a reduced ability to effectively increase the BoS following a gait perturbation, which highlights the role that age-related degeneration of the MTU capacities may play in recovery from unexpected perturbations. Despite the fact that the sample was intentionally homogenous (group of older female adults) and thus the variability was relatively low, we found significant positive correlations between ΔBoS at TD of the first recovery step and TS MTU capacities ($r = 0.57$ and $r = 0.53$ for the ankle plantar flexor muscle strength and AT stiffness, respectively), as well as with ΔMoS at TD of the first recovery step ($r = 0.50$ and $r = 0.41$), meaning that ~30 and 21% of the variability in ΔBoS and ΔMoS , respectively, during Reco1_L can be related to the variance in the TS muscle strength and AT stiffness within the examined group of older female adults (Fig. 5). Moreover, the multiple-regression analysis demonstrated that the ankle plantar flexor muscle strength and AT stiffness contributed from 27 to 37% to the MoS ($R^2 = 0.27$) and BoS ($R^2 = 0.37$). However, one might argue whether these static

measures can truly show the importance of TS MTU in recovering from sudden perturbations and whether the trip perturbation causes one to generate higher plantar flexion moments for creating a large anterior step, thereby increasing the BoS in response to a sudden perturbation to recover the dynamic gait stability. Because of the lack of direct joint moment assessment during the perturbation trials while walking on a treadmill, we therefore analyzed the EMG activity of two major plantar flexors (GM and SOL). When considering all subjects ($n = 22$) in the analysis of mean EMG_{norm} during the ankle push-off phase (50–100% of the ground contact phase) of Pert_R and comparing the perturbation trials with the baseline walking (please see Fig. 3), both GM and SOL showed a significantly higher mean EMG_{norm} during the push-off in *trial 1* (GM baseline vs. Pert_R in *trial 1*: 0.36 ± 0.09 vs. 0.76 ± 0.41 , $P = 0.007$ and SOL: 0.38 ± 0.08 vs. 0.67 ± 0.33 , $P = 0.005$). Furthermore, when comparing the two subject groups, GroupStrong, compared with GroupWeak, demonstrated a higher $\Delta\text{EMG}_{\text{GM}}$ during the ankle push-off phase of Pert_R throughout all the analyzed perturbation trials. Accordingly, it could be suggested that the observed greater TS muscle strength and higher AT stiffness in the stronger group may facilitate the generation of higher magnitudes and rates of ankle plantar flexion push-off moments, thereby creating more effective placement of the recovery limb following tripping. Previous studies using trip perturbations with younger and older adults seem to support this notion, because even though the muscular activity patterns (i.e., EMG trajectories over time) are similar between the different age groups, older adults seem to show a lower magnitude and rate of development of muscle activity (43) as well as lower ankle plantar flexion moment generation during the push-off phase (42) than their younger counterparts. Therefore, according to the present findings, the reduced ability to rapidly enlarge the anterior recovery step and effectively increase the BoS following gait perturbations seen in the elderly (49) may be more pronounced in weaker older adults, and this could be mainly due to lower ankle plantar flexion moment generation.

After repeating the unexpected gait perturbation, both groups (GroupStrong and GroupWeak) showed significantly higher ΔMoS at TD of Pert_R and Reco1_L in *trials 4* and *8* compared with *trial 1* (Fig. 6). This confirms earlier findings that adaptability to repeated perturbations seems to be preserved with human aging (2, 10, 13, 15, 30, 40). On the basis of the absence of warning about the perturbation and a very short duration between the onset of the perturbation and TD of Pert_R, it can be suggested that the adaptation seen at TD of Pert_R was primarily a result of reactive, feedback-driven adaptation. Therefore, these findings confirm previous reports (8, 40) that healthy older adults can adapt their reactive recovery response to repeated perturbations. Interestingly, despite the weaker subjects demonstrating significantly lower MoS values at TD for the analyzed recovery steps following the first perturbation trial (*trial 1*) compared with the stronger subjects, both groups increased their MoS at TD of Pert_R with a similar magnitude (Fig. 6) after repeated exposure to the mechanical perturbation (no significant differences between subject groups). Therefore, even though subjects with greater ankle plantar flexor muscle strength and AT stiffness display more effective stability recovery during an unexpected perturbation, this seems not to affect the ability to adapt the reactive recovery response to

repeated gait perturbations. Therefore, it can be assumed that even if TS MTU mechanical properties are important for the recovery from gait perturbations, they seem not to be the only major contributors to the plasticity of the reactive response during perturbation exposure. This is an important finding for clinical settings, as it can be suggested that older adults could benefit from perturbation training, despite the age-related degenerations in TS MTU capacities.

The outcomes of the present study may partly explain why exercise interventions (even if using combined strength and balance exercises) to date have resulted only in modest (~15%) improvements in fall incidence (17, 47). In the present study, significantly different recovery responses following an unexpected trip perturbation were identified between two groups of older adults with substantial differences in TS MTU mechanical properties (43 and 24% in maximal isometric ankle plantar flexion moment and AT stiffness, respectively). Accordingly, one might suggest that the exercise-induced improvements in the lower extremity MTUs in earlier exercise interventions may have been insufficient and that increases beyond a certain threshold have to occur to cause notable changes in stability. The facts that experiencing just a few slip perturbations can result in long-term (up to 12 mo) retention of the improvements in the reactive recovery response obtained in the acquisition session (5, 6, 39) as well as reduce daily-life falls up to 50% (36) and that an additional session can augment these retention effects (6) may explain why exercise programs that are more specific in challenging balance and use higher dose may have larger effects in fall prevention (46). Accordingly, improving not only the TS muscle strength but also the recovery mechanisms via more specific tasks to balance recovery responses may be beneficial for fall reduction and prevention.

With regard to our analysis of gait stability, one might argue that the subjects may have anticipated the onset of the perturbation and predictively adjusted their gait, thereby influencing the recovery performance. However, when analyzing the step before perturbation (TD of the left leg) for all eight perturbation trials, no clear predictive adjustments were observed (no significant differences in the MoS or BoS compared with baseline level) for either subject group. Despite the above arguments, however, the observed improvements in the recovery behavior may not be completely attributed to reactive, feedback-driven motor adjustments, because experiencing the perturbation task may alter and support (potentially undetected) feedforward adjustments, which are predominantly controlled by the cerebellum (34). Moreover, we cannot exclude the possibility that the improved reactive recovery response due to repeated practice was partly attributed to a heightened state of awareness and concentration in laboratory settings where perturbations occur. One might argue that the velocity of the treadmill (1.4 m/s) was not individually normalized and that the perturbation may possibly not have been equal for each participant. However, as no differences were found in the stability parameters (MoS or BoS) in the baseline walking or in their change due to perturbation (ΔMoS or ΔBoS) at TD of Pert_R between the groups, we believe that the selected velocity (equal to ~60% of maximal walking velocity) was appropriate to use in both groups of older adults, even if there was ~11% difference in the groups' average maximal walking velocities (2.54 ± 0.15 vs. 2.27 ± 0.21 m/s for GroupStrong and GroupWeak, respectively). Furthermore, it is

important to note that compared with our previous studies (30–32, 49), the change in MoS at TD of Pert_R relative to baseline (Δ MoS) was slightly lower in absolute terms [-0.15 ± 0.05 m in the present study vs. approximately -0.20 m given by McCrum and colleagues (30–32) and Süptitz et al. (49)]. This can be related to the specific perturbation systems (custom-built pneumatic brake-and-release system instead of earlier magnetic system) and hence to the resultant differences in perturbation magnitudes. Finally, as noted in MATERIALS AND METHODS, all participants had unilateral knee osteoarthritis (Kellgren-Lawrence score 2–3; no pain during locomotion) but were generally healthy compared with normative age group data. Considering that no differences were found in BoS, MoS, or temporal parameters of gait (contact times or swing times) in the baseline unperturbed walking when comparing the legs (affected and nonaffected), as well as the fact that the participants did not have pain during the perturbation trials, we believe that the participants were a representative sample and would not perform differently from older adults of the same age group without knee osteoarthritis, and therefore the findings of the present study could not be influenced by this drawback.

In conclusion, the results from the present study provide evidence that TS muscle weakness and a more compliant AT partly limit older adults' ability to effectively enlarge the BoS and recover dynamic stability after an unexpected perturbation during walking, increasing their fall risk. However, independent of TS MTU mechanical properties, older adults seem to be able to adapt their reactive response following repeated exposure to gait perturbations. Thus, to improve the ability to cope with unexpected gait perturbations and potentially reduce fall risk, older adults may benefit from both interventions targeting an increase in ankle plantar flexor muscle strength and AT stiffness and interventions targeting reactive recovery responses using repeated gait perturbations.

GRANTS

This work was supported by the Forschungsservicestelle, German Sport University Cologne (Hochschulinterne Forschungsförderung and Graduate Scholarship in Natural Science), and was rewarded with the Young Investigator Award by the German Society for Biomechanics. C. McCrum was funded by the Kootstra Talent Fellowship awarded by the Centre for Research Innovation, Support and Policy and by the NUTRIM Graduate Programme, both of Maastricht University Medical Centre+.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

G.E., G.-P.B., and K.K. conceived and designed research; G.E., A.M., M.L., and K.K. performed experiments; G.E., C.M., and K.K. analyzed data; G.E., C.M., G.-P.B., and K.K. interpreted results of experiments; G.E. and K.K. prepared figures; G.E. and K.K. drafted manuscript; G.E., C.M., A.M., M.L., G.-P.B., and K.K. edited and revised manuscript; G.E., C.M., A.M., M.L., G.-P.B., and K.K. approved final version of manuscript.

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